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FINAL REPORT

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NATIONAL AERONAUTICS & SPACE ADMINISTRATION

"DYNAMICS OF CAVITATING CASCADES"

by

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1. Introduction

This document represents the final report on Contract NAS 8-29313 with the National Aeronautics & Space Administration, George Marshall Space Flight Center, Huntsville, Alabama. The fundamental purpose of this contract was to study the unsteady dynamics of cavitating cascades and inducer pumps with a view to understanding (and possibly predicting) the dynamic characteristics of these devices. As a result of the present work we believe that significant advances have indeed been made toward this objective. Some evidence of this is the fact that we received the American Society of Mechanical Engineers Robert T. Knapp Award for publication [7].

The primary results of the work performed are contained in the publications listed at the end of this report. It would be superfluous to repeat all that technical material in this report since we believe that full documentation has already been achieved. However, it may be of some value to briefly review the chronology of the research and then summarize the final conclusions.

2. Review of Technical Progress

The initial contracts on this project were entirely concerned with theoretical analyses of the dynamics of cavitating cascades and inducer pumps. At that time it was widely believed that cavitating pumps could be modelled using simple L,R,C models and that progress only required sensible and accurate evaluation of the few key unknowns in these models such as the cavitation compliance. Our first few publications were directed toward that end. Types of cavitation occurring in cascades and inducer pumps were identified. Publications [1] and [2] presented quasistatic analyses and

results for the compliance resulting from attached blade cavities. Publication [3] presented analyses and results for the compliance characteristics of bubbly cavitation. Publication [4] extended the work of publications [1] and [2] to consider the truly dynamic rather than quasi-static effects for blade cavities. We still regard these efforts as having considerable merit; however, the results have to be seen in the wider context of pump dynamics as revealed in the later work particularly the experimental research.

The next step forward was the recognition of the need to define a more general form for the dynamics of a device like a cavitating inducer pump. The concept of the dynamic transfer function was the result of this work and was presented in Publications [6] and [7]. For example, these publications identified the need to evaluate the mass flow gain factor and presented analyses and results for the contributions to the mass flow gain factor due to attached blade cavities.

3. Experimental Measurements of Transfer Functions

Simultaneously it was recognized that real progress beyond this point could only be made if complete transfer functions could be measured experimentally. Consequently we embarked on an experimental program to accomplish this. A facility constructed for the express purpose of studying the unsteady, dynamic response of cavitating inducer pumps was constructed; it was called the Dynamic Pump Test Facility (DPTF). Details of this facility are primarily found in publications [8],[9], [11], [16], [17]. (Publication [5] resulted from one of the many instrumentation difficulties which had to be surmounted.) The facility as originally constructed utilized water and a number of 3 in. diameter impellers. Complete dynamic transfer functions for various mean flow conditions (including cavitation number)

over a range of frequencies up to 42 Hz. were presented in publications [8], [9] and [11].

The evidence of these transfer functions showed that

(i) even in the absence of cavitation the pump impedance departed significantly from its quasi-static value for reduced frequencies based on tip speed and blade spacing above about 0.03. The trends were consistent with those observed in some early dynamic measurements on centrifugal pumps made at NASA Lewis.

(ii) In the presence of even a modest amount of cavitation the dynamic characteristics became quite complex and none of the elements of the general transfer function could be regarded as negligible. As a result the simplistic L,R,C models appeared to be inadequate representations of the dynamic response.

(iii) Evaluation of the determinant of the experimentally measured transfer functions revealed that the inducer pump became increasingly "active" dynamic device as the cavitation number was reduced. Consequently, it would be capable of exciting instabilities in otherwise passive hydraulic systems.

4. <u>Bubbly Flow Model-Theoretical Transfer Functions</u>

The identification of the source of this active feature of cavitation dynamics and better understanding of the overall transfer functions became the next task. The result was the Bubbly Flow Model for the dynamics of cavitating pumps (Publication 12) which we believe to be the

best analytical approach to date. It yielded transfer functions which were in good qualitative and fair quantitative agreement with those measured experimentally. The model was based on a bubbly, two-phase flow representation of the flow in the blade passages of the inducer pump. Essential features were the dynamic waves in this flow caused by pressure fluctuations and the kinematic waves caused by fluctuating production of cavitation bubbles (in the vicinity of pump inlet) due, in turn, to the fluctuating flow rate. The latter phenomena is responsible for the active dynamic behavior of the pump in the model.

5. Further Experimental Transfer Functions

The first part of the experimental program involved measurements of the dynamic transfer functions for 3 in. diameter inducers in water at normal temperatures. Simple helical inducers as well as a scale model of the low pressure liquid oxygen turbopump inducer (LPOTP) in the Space Shuttle Main Engine were used. Questions then arose concerning (i) the manner in which this data should be scaled to larger inducers (ii) the scaling for other liquids given the fact that thermodynamic effects are often observed in the steady cavitating performance of inducers and (iii) the possible effects of non-uniform inlet flow on the transfer functions.

Consequently an alternative working section for the D.P.T.F. was designed and built which would allow measurements on 4 in. diameter inducers. Again the tests utilized several helical inducers as well as a 4 in. model of the LPOTP inducer. The results (which are presented in Publication 16) essentially indicated that we had anticipated the correct scaling laws when setting up the non-dimensionalization. There was substantial agreement between both sets of transfer functions and the bubbly

flow model. Indeed with the benefit of the earlier experiences the 4 in. transfer functions were probably more accurate and showed less scatter than the 3 in.transfer functions.

The results of tests designed to investigate the thermal effects (the water was heated to about 70°C) and the effects of non-uniform inlet flow are also presented in Publication 16. The answer was simply that virtually no effect was observed over and above the effects on mean flow performance.

6. Auto-oscillation Studies

The active dynamic feature of cavitating inducers which leads to instabilities in many applications could also be demonstrated in the DPTF. When the latter was operated under certain conditions without external perturbation of the flow the entire facility could become unstable resulting in large pressure and flow rate fluctuations. This instability which is referred to as auto-oscillation became the subject of an investigation parallel and complementary to the measurement of the transfer functions. Measurements of the frequency and onset cavitation number of auto-oscillation were made as well as the pressure and flow rate fluctuation magnitudes. This data is reported in publications [15], [17] and [18].

A primary objective of this work was to determine whether the frequency and onset cavitation number could be predicted from knowledge of the transfer functions over a range of cavitation numbers. This does indeed appear to be the case. The predicted frequencies were close to those observed and the scaling with inducer rotating speed and diameter conformed with expectations. The onset cavitation number could also be predicted but with less accuracy. Consequently auto-oscillation does appear to be

the outward manifestation of global instabilities caused by the active dynamic characters of cavitating inducers.

7. Unsteady Inlet Flow Characteristics

Additional studies of the details of the flow at or near inlet to a cavitating inducer were carried out because so much of the preceding research suggested that this was the crucial region insofar as the global dynamics were concerned. Detailed surveys of the axial and swirl mean velocity profiles were made (see publications 16,17,19). Unsteady pressure fluctuations on the walls of inlet duct were monitored at various axial locations during the auto-oscillation experiments (see publications 17,18, 19).

The general conclusion of these studies was that the complicated swirling flow at inlet which is integrally coupled with the backflow plays a major role in determining not only the steady state performance of the inducer but also its dynamic characteristics. Even in the absence of cavitation the dynamic response of such a swirling flow is not well documented and for this reason we undertook the theoretical analyses of wave propagation in such flows which are described in publication 19 and in an appendix to publication 17.

Although we believe we have knowledge of the global effects resulting from these flows it and that the detailed local measurements made thus far are valuable, it must be concluded that complete details remain to be uncovered. Specifically we would suggest a detailed survey of both the steady and unsteady flow velocity profiles in this region. We hope to complete such a survey of the unsteady flow velocity profiles as part of a separate study; the results will be reported to GMSFC.

8. Other Studies

Other kinds of flow involving phase change will probably exhibit the same kind of active dynamic characteristics demonstrated for cavitating inducers. One such example was investigated theoretically, namely a condensation or evaporation process in a pipe. The results were presented in publication 14 and provide a useful clue as to the source of the fluctuating energy injected by the inducer pump. In summary, any phase change process is capable of modulating a steady energy supply (for example, the energy released or absorbed during condensation or evaporation) into flow fluctuations.

9. Acknowledgments

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